Green House Gas Emissions

Comparative Life Cycle Assessment of Commonly Used Refrigerants in Commercial Refrigeration Systems*

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DOI: http://dx.doi.org/10.1065/lca2007.06.346

Please cite this paper as: Bovea MD, Cabello R, Querol D (2007): Comparative Life Cycle Assessment of Commonly Used Refrigerants in Commercial Refrigeration Systems. Int J LCA 12 (5) 299–307

Abstract

Background, Aim and Scope. In accordance with the Montreal Protocol and Kyoto Protocols, the refrigeration industry is currently evaluating the environmental performance of using HFCs and the so-called natural refrigerants, such as NH_3 or CO_2, as a long-term substitute for CFCs and HCFCs. The objective of this study is to quantify and compare the environmental impact throughout the life cycle of commercial refrigeration systems using HCFCs, HFCs and natural refrigerants.
The function of the system under study is the refrigeration of a standard European supermarket with an average surface area of 2000 m^2, with a cooling duty of 130 kW over a period of 15 years. Different scenarios have been created involving a combination of the most common refrigerants (HCFCs (R-22), HFCs (R-134a, R-404A, R-407A, R-407C, R-410A, R-507A) and natural ones (R-744 and R-717)), with different commercial refrigeration systems (direct expansion, secondary loop and distributed), for medium and low temperature. For each scenario, an environmental evaluation was carried out, using the Life Cycle Assessment (LCA) methodology, to compare the influence of both the refrigerant and refrigeration system on the overall contribution to impact.

Materials and Methods. According to ISO 1404X standards, the analysis is performed at the following two levels. 1) Firstly, the emissions accounted for in the inventory stage are sorted into impact categories according to CML to obtain an indicator for each category (mandatory elements). 2) Secondly, the weighting of environmental data to a single unit is applied (optional elements). In compliance with ISO 14042, a sensitivity analysis is performed and three different impact assessment methods (Eco-Indicator'95, Eco-Indicator'99 and EPS'00) are applied in order to analyse their influence on the results.

Results. The use of natural refrigerants such as R-744 and R-717 in direct expansion and secondary loop systems, respectively, is completely justified from the environmental point of view, taking into account that it offers better results for most impact categories and for all impact assessment methods. The need to promote the use of R-744 has to be stressed, despite the fact that it is presently in an experimental phase, and that its current installation outputs are low, since it has been demonstrated that it will perform better in direct expansion systems from an environmental point of view in a future scenario in which its efficiency equals that of R-404A, in the same way as what occurs with R-717 for secondary loop systems.The need to replace HCFCs by HFCs or natural refrigerants is clearly shown by the contribution to the ozone depletion category.

Discussion. Energy efficiency of a refrigeration installation is a determinant parameter to assess pollutant emissions to the environment. If we assume a future scenario in which R-744 has an efficiency similar to that of R-404A, then R-744 is seen as the refrigerant which offers a better environmental behaviour in the direct expansion system.

Conclusions. It can be concluded that this study demonstrates how using the so-called natural refrigerants as a long-term substitute for CFCs and HCFCs, even better than the use of HFCs, is environmentally feasible.

Recommendations and Perspectives. More investment and research should be carried out with the aim of promoting the use of the so-called natural refrigerants to fulfil the Montreal and Kyoto Protocols. The technology used for R-744 is at a developmental stage, and presently, the efficiency of the installations operating with this refrigerant is lower than those others functioning with HFCs or R-717. In the near future, it will be demostrated that this natural refrigerant can replace the use of other HFCs.

Keywords: Commercial refrigeration; comparative LCA; HCFCs; HFCs; Kyoto Protocol; Montreal Protocol; refrigerants

Introduction

The World concern about the greenhouse effect enhancement due to anthropogenic causes is reflected in the enactment of the Kyoto Protocol (1997) and Montreal Protocol (2000). This environmental problem is transferred to the field of refrigeration and air conditioning with two main aspects: the direct effect due to the environmental emissions of the most commonly used refrigerant, the HFC fluid family, which are listed into the basket of seven greenhouse gases published in the Kyoto Protocol, and the direct effect caused by energy consumption of cooling facilities.

In order to correct this environmental problem produced by cooling plants, numerous lines of research are being considered which may be classified into two categories:

– Those that attempt to mitigate the direct effect by using new refrigerant fluids which are harmless for the greenhouse effect, and are the so-called alternative refrigerants. Otherwise, through the devising of methodologies, and functioning and usage systems to avoid emissions of HFC fluids to the environment.

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– Those that attempt to improve the efficiency of the frigorific cycle of vapour compression by either modifying or implementing systems with greater energy efficiency.

In order to focus the problem, we have confined our study to the application of commercial refrigeration in supermarkets since artifical cooling production application fields are numerous, just as the used refrigerant fluids are. The reason to select this particular application is because the power consumption of a supermarket is between 400 and 1,000 kWh/m²/year, which makes it a commercial building with a very high energy intensity, and between 35% and 50% of this power consumption is destined to the cooling plant (Billiard 2003, Lundqvist 2000). This fact, linked to the vast expansion of supermarkets which already covers 70% of the food sales market in Europe with more than 44000 centres opened, has led to these commercial buildings becoming an important power demand agent in any nation, as the following fact reveals: 5% of energy produced in the United Kingdom is consumed by supermarkets. Globally on the other hand, commercial refrigeration is the refrigeration subsector with the largest refrigerant emissions calculated as CO_2 equivalents, representing 40% of total refrigerant emissions (IPCC 2005).

This work has assessed and compared the environmental impact of those refrigerants usually employed in commercial refrigeration (HFCs and HCFCs), as well as those that are taken as firm candidates to replace them (the so-called natural refrigerants, such as NH_3 (R-717) or CO_2 (R-744)) by applying the Life Cycle Assessment Metholodology. This work method has already been used by other authors to assess the impact of refrigerants used in other fields (Clarke 1997, Johnson 1998, Ciantar 2000), and which are also recommended by the Intergovernmental Panel on Climate Change (IPCC 2005), since they allow for a more complete analysis of environmental problems than the majority of studies undertaken to date, which only consider either the direct or indirect impact on the greenhouse effect.

1 Materials and Methods

1.1 Description of the scenarios

Following the analysis undertaken in other studies (Little 2002, IPCC 2005 or Sand et al. 1997), three different parameters ought to be taken into account in order to design the scenarios:

– Refrigeration system: Three technology alternatives can be used for commercial refrigeration: direct expansion system (DX), secondary loop systems (SEC) or distributed systems (DIST).
– Range of temperature: Medium temperature (MT) (fresh food loads, ranging from –2°C to –7°C) and low temperature (LT) (frozen food loads, ranging from –18°C to –32°C).
– Refrigerant: The most widely refrigerants applied to commercial refrigeration are: HCFCs (R-22), HFCs (R-134a, R-404A, R-407A, R-407C, R-410A, R-507A) and natural ones (R-717 and R-744).

According to the feasible combination of the three above-mentioned parameters, the scenarios shown in **Table 1** will be analysed.

1.2 Goal and scope definition

The objective of the study is to analyse the effects that refrigerants used in commercial refrigeration have on the environment, specifically on their use in food conservation in supermarkets, on the medium temperature (from –2 to –7°C), and on the low temperature (–18 to –30°C). Different combinations of refrigerants and refrigeration systems, as described in Table 1, will be analysed for both these temperature ranges. From an environmental point of view, special attention will be paid to the feasility study concerning the use of HFCs and the so-called natural refrigerants, such as R-717 or R-744, as a long-term substitute for CFCs and HCFCs in commercial refrigeration systems.

The following life cycle stages of a commercial refrigeration system have been considered in the study:

– extraction of the raw materials needed to produce each refrigerant.
– production of the refrigerant (both its initial charge and its replacement due to leakages).
– use and maintenance. Other than the power consumption needed for the installation to function, the fact that leakages are produced while the installation is used has to be taken into account, and these must be replaced by a new refrigerant.
– waste recovery considering that 100% of the refrigerant is recovered at the end of its life span (Little 2002).

The installation (machinery) required for refrigeration production is beyond the scope of this study.

The basis of the system is to cool either refrigerated foods (medium temperature) or frozen foods (low temperature). The size of the supermarkets depends on the country considered. The average supermarket size in the USA has changed from 2,300 m² in 1997 (Sand et al. 1997) to 5,400m² in 2002 (Little 2002), whereas an average supermarket size in Europe is somewhere between 1,000 m² and 2,500 m².

Table 1: Description of scenarios

	Refrigerant								
	HCFCs	HFCs						Natural	
System	**R-22**	**R-134a**	**R-404A**	**R-407A**	**R-407C**	**R-410A**	**R-507A**	**R-717**	**R-744**
Direct expansion (DX)	MT	MT	MT, LT	LT	LT	MT	MT, LT	–	MT, LT
Secondary loop (SEC)	MT	MT	MT, LT	LT	LT	MT	MT, LT	MT, LT	–
Distributed (DIST)	MT	MT	MT, LT	LT	LT	MT	MT, LT	–	–

MT: medium temperature
LT: low temperature

Table 2: Life cycle inventory data for each scenario

		Medium Temperature (MT)						Low Temperature (LT)				
		R-22	R-134a	R-404A	R-410A	R-507	R-744	R-404A	R-407A	R-407C	R-507	R-744
direct expansion (DX)	Initial charge (kg refrigerant)	401.8	407.0	354.5	360.0	356.0	254.0	283.0	313.0	308.0	284.0	201.6
	Leakage* (kg refrigerant)	813.6	824.2	717.9	729.0	720.9	514.4	573.1	633.8	623.7	575.1	408.2
	Emissions [a,b] (kg CO_2 eq.)	1383196.5	1071427.5	2340231.8	1261170.0	2378970.0	0.0	1868224.5	1121870.3	954261.0	1897830.0	0.0
	Energy [a] (kWh)	2619762.4	2847322.4	2757563.0	2645949.2	2686536.1	4106192.9	1464267.0	1510561.0	1559878.0	1464267.0	1720026.0

		Medium Temperature (MT)						Low Temperature (LT)				
		R-22	R-134a	R-404A	R-410A	R-507	R-717	R-404A	R-407A	R-407C	R-507	R-717
Secondary loop (SEC)	Initial charge (kg refrigerant)	44.2	44.8	39.0	39.6	39.1	22.3	30.1	34.4	33.9	31.2	17.7
	Leakage [a] (kg refrigerant)	26.5	26.9	23.4	23.8	23.5	13.4	18.7	20.6	20.3	18.7	10.6
	Emissions [a,b] (kg CO_2 eq.)	45124.8	34944.0	76284.0	41104.8	77418.0	0.0	60831.6	36532.8	31120.2	61776.0	0.0
	Energy* (kWh)	3064925.5	3332014.8	3226185.7	3096065.5	3143488.8	3137604.0	1689215.4	1742479.0	1799210.9	1689215.4	1653121.1

		Medium Temperature (MT)					Low Temperature (LT)			
		R-22	R-134a	R-404A	R-410A	R-507	R-404A	R-407A	R-407C	R-507
Distributed system (DIST)	Initial charge (kg refrigerant)	99.7	101.0	98.6	89.9	89.0	70.9	79.2	77.8	71.9
	Leakage [a] (kg refrigerant)	74.8	75.8	66.5	67.4	66.8	53.2	59.4	58.4	53.9
	Emissions [a,b] (kg CO_2 eq.)	127130.3	98475.0	216627.0	116645.3	220275.0	173350.5	105138.0	89275.5	177952.5
	Energy consumption[b] (kWh)	2977677.5	3236481.5	3134933.0	3007853.7	3054282.4	1600071.5	1650805.4	1704862.0	1600071.5

[a] During the system's life span (15 years)
[b] Global warming emissions due to leakage during the system's life span (kg CO_2 eq.). See conversion parameters in Table 3

For our study purpose, we will consider an average European supermarket with an average sales area covering 2,000 m² (by assuming the tendency of recent years indicating marks the increase of area of such premises), with a useful life of 15 years.

For each scenario described in Table 1, **Table 2** shows the assignments given to the functional unit of each life cycle stage (see **Table 3** for conversion parameters).

2 Results

2.1 Life cycle inventory

A life cycle inventory has been carried out for each refrigerant to be compared in this study. By way of example, **Fig. 1** and **2** illustrate the inventory data considered for refrigerants R-22 (Campbell & Mc Culloch 1998) and R-134a (Mc Culloch & Lindley 2003), respectively, in DX systems with a medium temperature. Similar inventories are obtained for the remaining refrigeration systems as well as for the low temperature option by taking the charge values, emissions and energy as shown in Table 2. For the remaining refrigerants, R404A, R407A, R407C, R410A and R507, there are no data available referred to their manufacturing process. Therefore, to do the life cycle inventory of those refrigerants we have solved this lack of information referring our data to the R134a and correcting them with a particular increment for each one, as Little (2002) suggests. The correcting increments are shown in **Table 4**. The inventories corresponding to the natural refrigerants R-717 and R-744 have been obtained by BUWAL250 (1998), where the manufacture of R-717 is obtained by the steam reformer method, and where R-744 is a co-product (Coray 1993).

Table 4: Increase greenhouse effect gases on R-134A emissions (Little 2002)

Refrigerant	Increment
R-404A	9 kg CO_2/kg R-404A
R-407A	5 kg CO_2/kg R-407A
R-407C	4 kg CO_2/kg R-407C
R-410A	5 kg CO_2/kg R-410A
R--507A	9 kg CO_2/kg R-507A

Table 3: Characterization factor for global warming potential (GWP 100 years) (Sand et al. 1997)

	R-22	R-134a	R-404A	R-407A	R-407C	R-410A	R-507A	R-717	R-744
Factor	1700	1300	3260	1770	1530	1730	3300	0	1

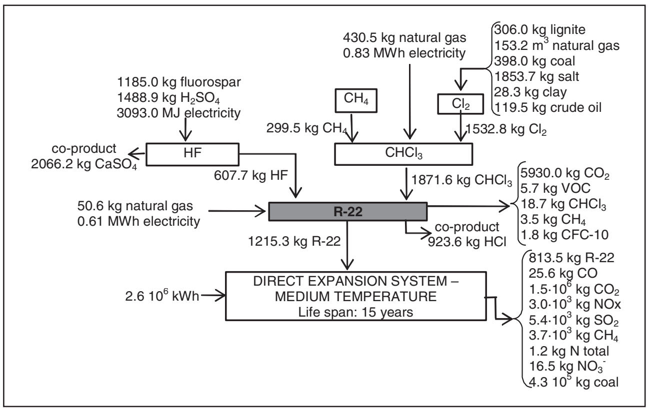

Fig. 1: The LCI of R-22 for a DX-MT system

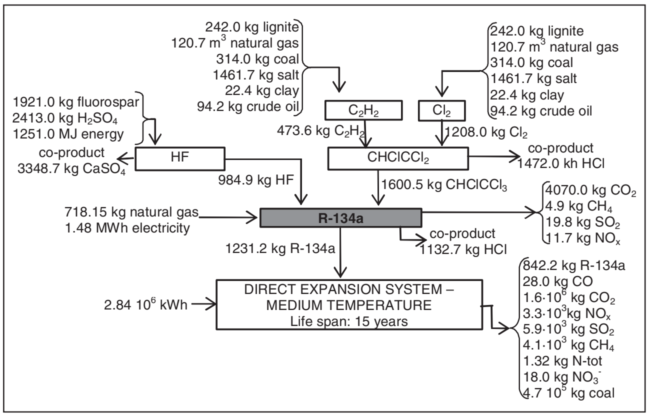

Fig. 2: The LCI of R-134 for a DX-MT system

Table 5: Reference combination of primary energies within the Spanish electricity grid in 2004 (REE 2004)

Primary energy	%
Coal	37.23
Fuel oil	2.14
Natural gas	1.82
Combined cycle	14.90
Nuclear	30.54
Hydropower	13.37

The inventory data used for the generation of electrical energy corresponds to the primary energy structure used by the Swiss Federal Institute of Technology (ESU-ETHZ) (Frischknecht et al. 1995). **Table 5** shows the energy grid mix used to generate Spanish electricity during the year 2004.

2.2 Life cycle impact assessment

Once each scenario described in Table 1 has been modelled in the SimaPro software (2001), impact assessment is performed following ISO 14042 (2000) instructions. Life cycle impact assessment(LCIA) results will be analysed at two levels:

– Firstly, the emissions accounted for in the inventory stage have been arranged into impact categories according to CML (Guinee 2001) to obtain an indicator for each category.
– Secondly, the weighting of environmental data to a single unit will be applied. A wide range of weighting methods exist and several reviews can be found in Baumann and Rydberg (1994), Eriksson et al. (1996), Giegrich and Schmitz (1996), Powell et al. (1997), Hertwich et al. (1997), Dreyer et al. (2003) or Bovea and Gallardo (2006). Three different impact assessment methods have been applied which are compatible with ISO 14042 (2000) to select which alternative scenario has a better overall environmental performance: Eco-Indicator'95 (EI'95) method (Goedkoop 1996), Eco-Indicator'99 (EI'99) method (Goedkoop and Spriensma 2000) and Environmental Priority System (EPS'00) method (Steen 1999a,b), and a sensitivity analysis is carried out to verify the effect that each has on the final result.

The results are shown separately for both medium and low temperatures.

2.2.1 Analysis by impact category

The emissions accounted for in the inventory stage have been allocated into five impact categories: global warming, ozone layer depletion, photochemical oxidation, acidification and eutrophication, according to CML (Guinee 2001). The contributions to each are shown in **Fig. 3a–e** and **Fig. 3f–j** for medium temperature and low temperature, respectively.

The following is obtained for the medium temperature results:

– The DX refrigeration system performs better than the SEC and DIST systems for the impact categories of photochemical oxidation (see Fig. 3c), acidification (see Fig. 3d) and eutrophication (see Fig. 3e), except for R-744. This is due to a lower energy consumption of this system as opposed to SEC or DIST (see Table 2). With the exception of R-744, contributions to the impact category of global warming (see Fig. 3a) are greater for all refrigerants due to the fact that this system uses larger charges of refrigerants than the other two do (see Table 2). These contributions are maximum for R-404A and R-507 due to their greater characterization factor for global warming potential (see Table 3). R-22 presents significantly higher values for ozone depletion potential (see Fig. 3b) since it is a HCFC refrigerant which includes chlorine.
– The DIST and SEC systems have very similar values for all impact categories, although these values are slightly higher for R-507 in the DIST system, and for R-134a in the SEC system. In both systems, R-22 has higher values for the ozone layer depletion potential than the remaining refrigerants.
– With regard to natural refrigerants, R-717 (SEC system) is seen to present results which are close to those of R-410A for all impact categories. R-744 (DX system) presents greater contributions to the impact categories of photochemical oxidation (see Fig. 3c), acidification (see Fig. 3d) and eutrophication (see Fig. 3e) than the remaining refrigerants do. This is due to the low ratio between the frigorific power produced and the electric energy absorbed (COP), which increase energy consumption. This aspect will be discussed in further detail in the following section.
– Generally, it can be stated that R-410A offers good results for all impact categories and for the three refrigeration systems.

The following is obtained for low temperature results:

– In the DX system, the refrigerants with the best results are R-404A and R-507 for all imapct categories except

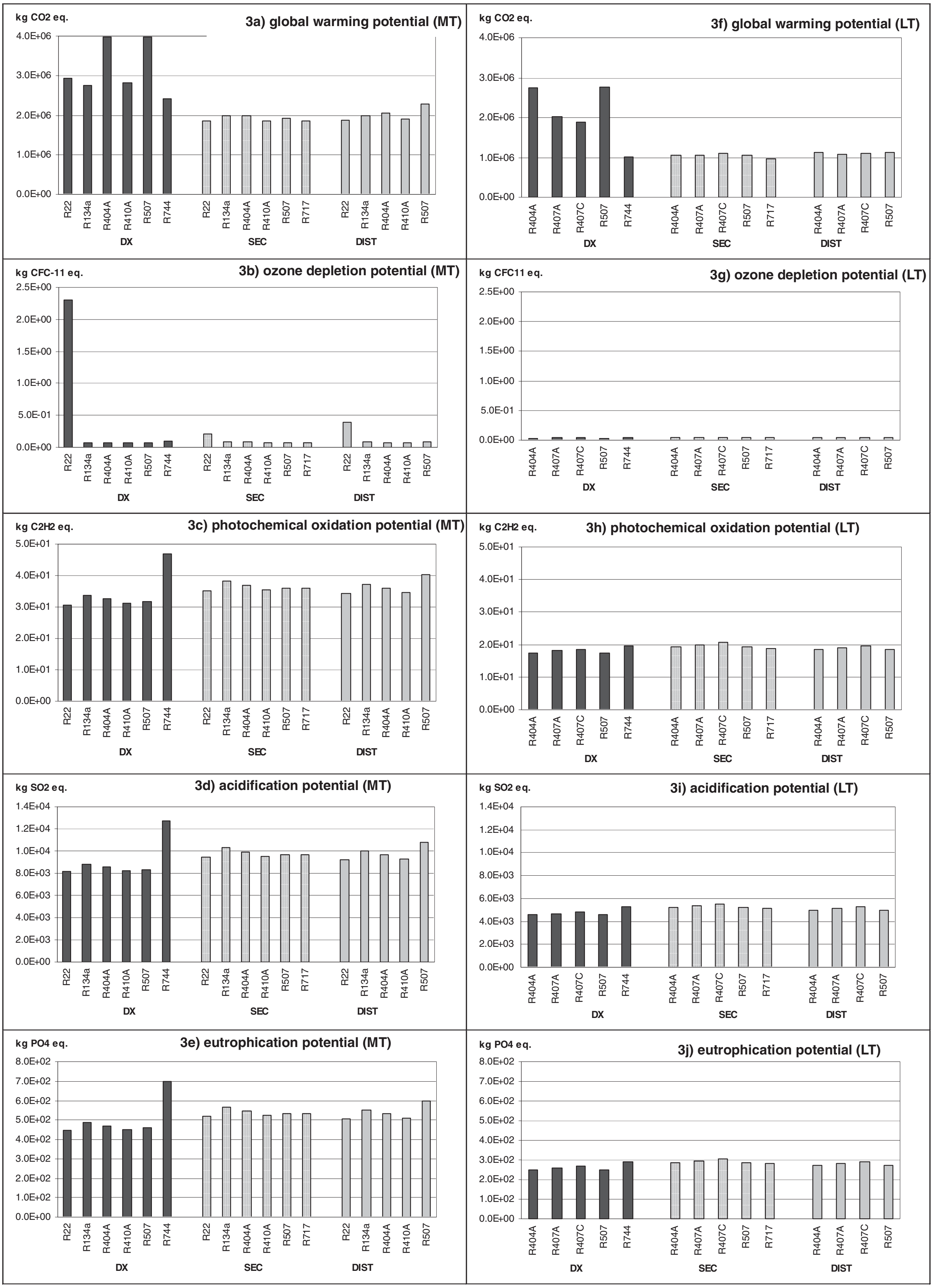

Fig. 3: LCIA results by impact category

for the global warming potential, which obtains higher values than the rest.

– Likewise, the SEC or DIST systems are preferable from the global warming category perspective (see Fig. 3f), which have very similar values to those of the DX system, since the former systems present lower values in relation to the initial charge and refrigerant leakages (see Table 2). It should be stressed that R-744 in the DX system presents similar values to the remaining refrigerants in the SEC and DIST systems.
– R-717 presents better values than the remaining refrigerants for all impact categories within the SEC system.
– Overall values in the DIST system are lower than the SEC system, and the refrigerants that offer better results for all impact categories are R-404A and R-507.

2.2.2 Analysis by impact assessment method

As there are no criteria to select the best weighting method, the three impact assessment methods (Eco-Indicator'95, Eco-Indicator'99 and EPS'00) have been applied and tested in parallel to explore whether results differ. Results reported in **Fig. 4a–c** and **Fig. 4d–f** have been obtained, for medium and low temperatures, respectively.

A similar profile is obtained with the three impact assessment methods for the SEC and DIST systems, while major differences can be obtained with the EPS'00 method for DX systems, mainly for R-404A and R-507 (see Fig. 4c and Fig. 4f). This fact is because the refrigerants R-404A and R-507 present considerably higher characterization factors for the global warming potential than the remaining refrigerants do (see Table 3) and also to the fact that the EPS'00 method has a greater influence in relation to gas emissions which contribute to the greenhouse effect, as the values in **Table 6** show.

Table 6: Comparison of environmental weights (after characterization, normalization and weighting) normalized to CO_2=1

	CO_2	NO_x	SO_x	NH_3
EI'95	1.00	414.66	743.46	1099.48
EI'99	1.00	531.71	280.49	700.00
EPS'00	1.00	19.54	30.00	26.61

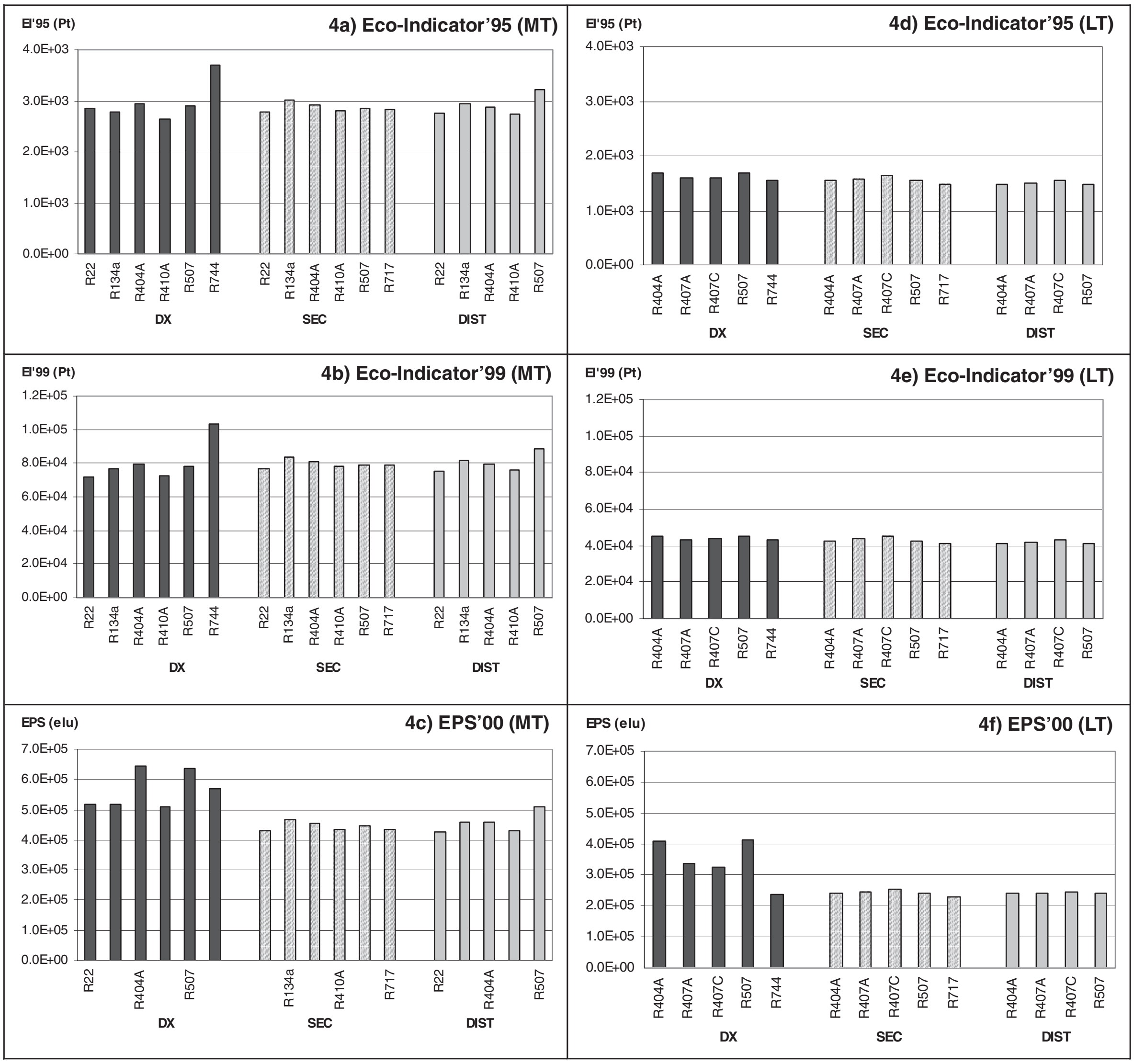

Fig. 4: LCIA results by impact assessment methods

The DX system assessed with the EPS'00 method presents better results than either the SEC or DIST system due to this system's characteristics (longer conductions and more connections), which not only requires greater initial charges of refrigerants, but also produces greater leakages (see Table 2) than the SEC and DIST systems, which lead to a greater greenhouse effect of gas emissions.

Despite these differences, the following conclusions may be drawn:

– On average, at the medium temperature (see Fig. 4a–c), the SEC system offers lower contributions to the impact than DIST and DX, respectively. In relation to refrigerants, R-410A and R-22 offer the best results for all three refrigeration systems and for the three impact assessment methods. It has to be taken into account that it will be forbidden to use R-22 (HCFC) as from the year 2030 (Kyoto Protocol 1997). As far as natural refrigerants concern, R-717 in the SEC system performs similarly to R-410A, whereas R-744 in the DX system behaves worse due to its current low energy efficiency (see Discussion).
– On average, the low temperature (see Fig. 4d–f) in the DIST system offers better results than the SEC and DX systems, respectively. As for refrigerants, natural refrigerants (R-744 and R-717) present the best results for the DX and SEC systems, whereas R-404A and R-507 offer the best results in the DIST system.

3 Discussion

From the results for natural refrigerants in the previous section, it is observed that R-717 presents a lower contribution to the impact, both for impact categories as well as impact assessment methods for the SEC systems, than the remaining refrigerants, and it is only equalled or slightly improved by R-410A. R-744 in the DX with a LT presents the least results in the study by impact assessment methods, which are slightly higher in the analysis by categories. Nonetheless, this refrigerant at a MT displays the worst results in all the assessment methods used, except for the EPS'00 indicator, and this fact is justified. However, this does not occur with R-744 in the DX systems.

Due to the recently utilization of the R-744 as refrigerant, the technology developed for using this working fluid is still in a very incipient stage, so the energy efficiency achieved with those facilities is lower than that achieved with other refrigerants used during more time. The energy efficiency of a refrigeration installation is a determinant parameter to assess pollutant emissions to the environment, as deduced from the data shown in Table 2 and Fig. 1. Therefore, to complete the comparative life cycle analysis, we have made the assumption that the refrigeration facility that works with R-744 attains an energy efficiency equivalent to those that works with R-404A, as Girotto (2004) makes probable. By this way, we have moved into a most likely near scenario, where energy efficiencies obtained with all refrigerants are quite similar.

Therefore, if we assume that the R-744 output will be similar to that of R-404A in the near future at both a low and medium temperature, the life cycle inventory data initially included in Table 2 are now as shown in **Table 7**.

By analysing the environmental impact of these two scenarios, the current scenario with the data in Table 2 and the future scenario with the data in Table 7, the results of **Fig. 5** and **Fig. 6** are obtained per impact categories and impact assessment methods, respectively.

Table 7: Life cycle inventory data for R-744 (future scenario)

	R-744 Future scenario	
Direct expansion (DX)	**MT**	**LT**
Initial charge (kg refrigerant)	254.0	201.6
Leakage [a] (kg refrigerant)	514.4	408.2
Emissions [a,b] (kg CO_2 eq.)	0.0	0.0
Energy[a] (kWh)	2757443.4	1506103.5

[a] during the system's life span (15 years)
[b] global warming emissions due to leakage during the system's life span (kg CO_2 eq.). See conversion parameters in Table 3

When the results obtained with the future scenario for the impact categories (see Fig. 5) are compared with those previously obtained in Fig. 3, it is observed that R-744 improves the performance of the remaining refrigerants in the DX system for the global warming and ozone depletion categories, whereas it is equalled by the remaining categories. Similar conclusions are obtained when comparing the results obtained by impact assessment methods (see Fig. 6 and Fig. 3), where R-744 is seen as the refrigerant which offers a better environmental behaviour in the DX system.

In addition to the previous comments regarding to the energy efficiency of the system, it is important to remark the possible influence that the energy grid mix could have on results, due to the large electricity consumption by the refrigeration units.

4 Conclusions

Commercial refrigeration installations cause impacts on the environment, mainly due to the action of refrigerants used and to the power consumption of the cooling production installation. The Life Cycle Assessment Methodology applied to refrigeration in supermarkets enables us to make a comparison among three refrigeration systems (direct expansion, secondary loop and distributed), and among three groups of refrigerants (HCFC, HFC and natural refrigerants) at both a medium and low temperature in two described scenarios – present and future – in which the energy outputs of R-744 equal those of R-404A.

The most significant conclusions obtained from this study are:

– In relation to refrigerants:
  - It is necessary to promote the substitution of HCFCs by either HFC or natural refrigerants to reduce their contributions to the impact category of ozone layer depletion (see Fig. 3b).
  - Taking into account the impact categories considered in the Montreal and Kyoto Protocols (global warming and ozone layer depletion), the use of natural refrigerants such as R-744 and R-717 in DX and SEC systems, respectively, is justified. The need to promote

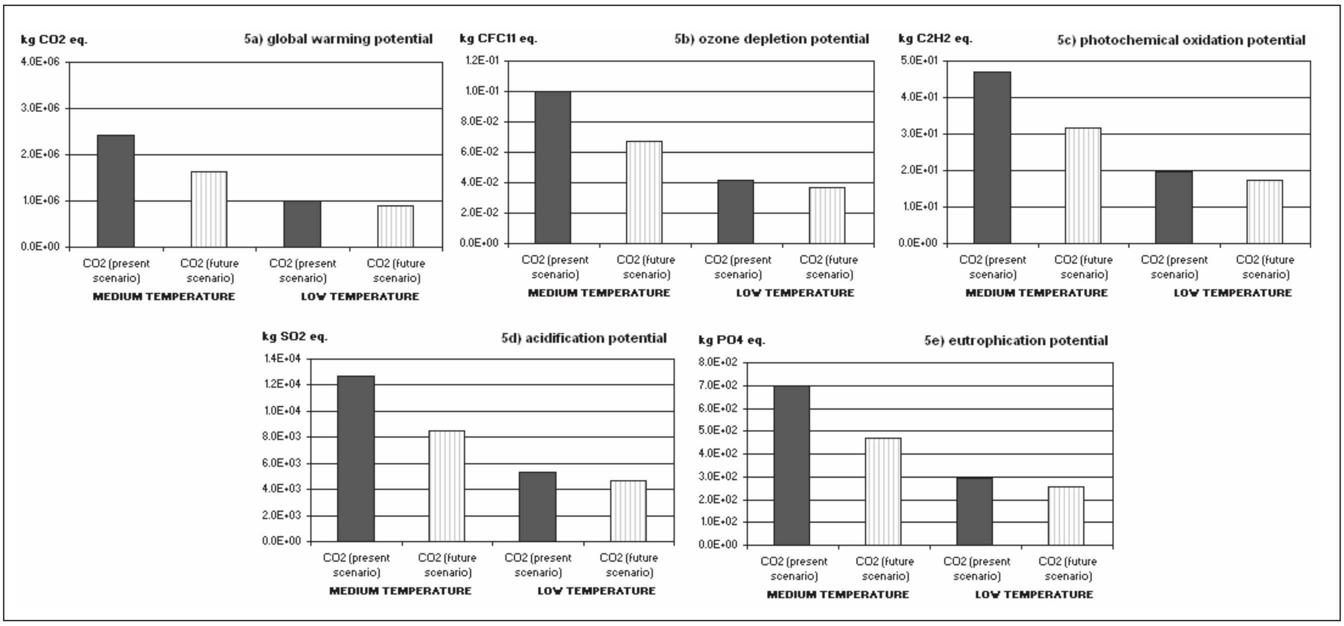

Fig. 5: Comparison of LCIA results among present and future scenarios for R-744 in DX system by impact category

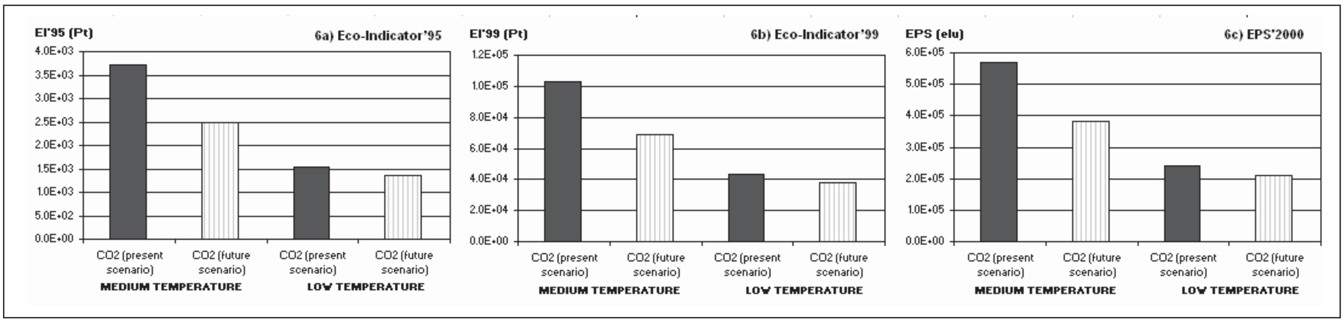

Fig. 6: Comparison of LCIA results among present and future scenarios for R-744 in DX system by impact assessment methods

the use of R-744 has to be stressed, which despite being in an experimental phase and its present installation outputs are low, will perform better from an environmental point of view in the DX systems in a future scenario in which it equals the efficiency of that of R-404A, in the same way as what already occurs with R-717 for the SEC systems.

- Good environmental results are obtained for both Eco-Indicador '99 and CML method at a medium temperature under current refrigerant R-410A conditions, along with R-22 in a direct expansion system. It should be stressed that R-410A has a short life in the atmosphere, a low GWP and a good output value or refrigerant fluid efficiency (COP). However, R-22 is a HCFC-type refrigerant with a ozone layer depletion potential and its worldwide use will cease in the year 2030. In SEC, R-717 presents good environmental results at a medium temperature and better results at a low temperature. R-744 presents the best results at both a medium and low temperature and for all refrigeration systems in a future scenario in which it may equal the energy outputs of those of R-404A. As for the low temperature, R-404A and R-507 in SEC and DIST obtain the best environmental results, and they also have the best COP values.

– As for the refrigeration system:
  - It is important to control both power consumption and refrigerant leakages caused by installation use since this is stage with a greater impact contribution.
  - Power consumption depends on the refrigeration system and the energy output of the refrigerant used. Out of the three systems analysed, SEC has a higher consumption of 17%, and DIST has a 14% greater consumption than the DX at a medium temperature. Therefore, CO_2 emissions, the so-called indirect emissions since they are due to power consumption, represent 85% of SEC emissions and 87% of DIST emissions in a DX system. At a low temperature, SEC system power consumptions are 12% higher than DX, whereas the DIST system is 6% higher than DX. Therefore, indirect DX system CO_2 emissions represent 89% of SEC emissions and 94% DIST emissions.
  - Since the DX systems have longer conductions and more connections, they need greater charges of refrigerant and they have considerably greater leakages than the remaining systems have, that is, 13.5% of the charge as opposed to 4% of the SEC system and 5% of the DIST system, respectively. Leakages result in the greenhouse effect of gas emissions to the atmo-

sphere whose impact is compared with the CO_2 effect. These direct emissions are expressed in kg of CO_2 are at medium and low temperatures 3.5% of DX for the SEC systems, and are 9.5% of DX for the DIST systems. This value also depends on the characterization factor for the global warming potential of the refrigerant used, where natural refrigerants or the HFCs with a lower factor (R-134a, R- 410A, R-407A and R-407C) are recommended.

- To summarise, the DX systems have less indirect CO_2 emissions but higher direct emissions in relation to the remaining systems at both a low and medium temperature. For the DX systems, direct emissions are between 40% and 60% of the total depending on the type of refrigerant, whereas the figures are only 4% for the SEC system and only between 6% and 10% for the DIST system. Overall CO_2 emissions in the SEC and DIST systems are between 50% and 65% of the DX systems emissions, depending on the GWP value function of the refrigerant.

5 Recommendations and Perspectives

The Montreal and Kyoto Protocols have sparked off a technological shift in the international refrigeration and HVAC (Heating, Ventilation, Air Conditioning) industry to reduce the direct and indirect emissions of ozone depleting and global warming substances. The industry, research institutes and universities related to this knowledge field have to undertake a big effort to bring forward new knowledge, technology and practical solutions, in the way that the society could carry out the extensive changes necessary within reasonable expenses.

Natural refrigerants are working fluids that accomplish the new environmental requirements. In particular, the R-744 (CO_2) combine its excellent environmental properties with standing out security and heat transfer properties, what allows to use this refrigerant in a wide range of appilications: HVAC, commercial and transport refrigeration, automotive climatization, etc. The main obstacle to market refrigeration and climatization facilities working with R744 is its low efficiency.

Nowadays, the technology used for R-744 is at a developmental stage, and presently, the efficiency of the installations operating with this refrigerant is lower than those others working with HFCs or R-717 (NH_3). However, areas of improvements are identified and research work must be done to improve the system and constituting components.

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Received: July 5th, 2006
Accepted: June 21st, 2007
OnlineFirst: June 22nd, 2007